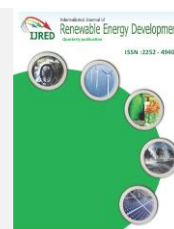




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Research Article

Optimization of Aeration for Accelerating Municipal Solid Waste Biodrying

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Abstract. Biodrying technology is commonly used in Thailand to produce refuse-derived fuel (RDF), however, this technology remains ineffective on high-moisture waste. Air supply is key to ensuring homogenous temperature development within the waste matrix during biodrying, increasing RDF quality. This study investigated negative aeration during local municipal solid waste biodrying to meet RDF standards in reduced time. Lysimeter experiments were performed on pre-shredded waste (300 kg/m³) using different aeration patterns. The temperature, vent gas oxygen level, weight loss, and leachate volume during the biodrying process were monitored. In addition, the treated waste's temperature, moisture, and heating values were evaluated to determine the biodrying process efficiency. The results indicate that shorter heating phases can be achieved during continuous aeration. No significant temperature variation was observed in the waste layers, with a low standard deviation of 1.96% during constant air supply, indicating homogeneous temperature development during the biodrying process. The vent gas contained 15–20% oxygen and non-detectable methane, evidencing sufficient air supply. The total heat development was independent of aeration pattern; therefore, biodrying was unaffected by excess air supply at a 95% confidence level. The highest weight loss and moisture content reduction were 25% and 66%, respectively. The optimal aeration was continuous mode with non-excessive aeration, increasing the lower heating value from 2,884.0 to 4,938.0 kCal/kg, and reducing the moisture content from 48.5% to 22.2%. RDF quality can be improved 1.7 times to meet Thailand's standards within a short biodrying period of 7 days using homogeneous temperature distribution operated under continuous aeration.

Keywords: Biodrying; mechanical biological treatment; municipal solid waste; negative aeration; refuse-derived fuel



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1. Introduction

The rapid increase in municipal solid waste (MSW) has raised major concerns globally. Waste generation is commonly influenced by population growth and the increasing consumption of goods to meet the needs of a larger population. The World Bank estimates that annual MSW generation will increase from 2.01 billion tonnes per year to 3.40 billion tonnes between 2018 and 2050, correlating to forecasted global economic growth. Meanwhile, the total quantity of waste generated in low-income countries is expected to increase more than threefold by 2050, with food and green waste expected to constitute more than 50% of total waste in low- and middle-income countries (Kaza *et al.*, 2018).

Globally, around 37% of waste is disposed of in various types of landfills, whereas 33% is illegally dumped, 19%

undergoes material recovery through recycling and composting, and 11% is treated through modern incineration (Kaza *et al.*, 2018). MSW disposal, either in sanitary landfills or open dumpsites, is the most popular method for processing MSW due to its simple operation and low cost, especially in low- and middle-income countries. However, poor waste management in these sites has resulted in numerous environmental problems, including soil and water pollution and greenhouse gas emissions (Korai *et al.*, 2016). MSW in landfills is the third-largest source of global methane emissions, accounting for approximately 550 Tg annually (Zuberi and Ali, 2015). However, limitations in land area and public opposition are also slowing down the increase and expansion of MSW disposal sites.

To address waste disposal problems, the use of MSW as raw material in waste-to-energy facilities can help to

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divert MSW from traditional disposal processes. Moreover, the use of alternative energy sources for electricity production has been increasingly promoted in recent years (e.g., Buyukkseskin *et al.*, 2019) and MSW can be considered an important renewable energy source to reduce oil and coal consumption. In this context, mechanical and biological treatment (MBT) has been introduced as a low-cost MSW pre-treatment approach to producing refuse-derived fuel (RDF), a carbon-neutral renewable energy source (Ngamket *et al.*, 2021; Hao *et al.*, 2018). Among the various MBT technologies applied to RDF production, biodrying has been developed to process MSW with high moisture content. Biodrying is an aerobic bioconversion process that uses self-generated heat produced by microbial biochemical processes to evaporate moisture from biowaste with high water content for subsequent disposal, including incineration, landfill disposal, or the production of RDFs (Ma *et al.*, 2019).

In the biodrying process, water evaporation and mass transfer conditions are improved through aeration. The porosity of waste materials enables air to enter the waste, absorb moisture, and carry the water to the atmosphere. The remaining organic materials are then dried and stabilized, and the final product can be used as solid recovered fuel (Latosińska *et al.*, 2022). The main objective of biodrying is to treat waste and rapidly produce high-quality. After biodrying, the RDF product can be used as an energy source for safe and economical combustion in biomass boilers or cement kilns (Ngamket *et al.*, 2021). Furthermore, RDF derived from biodrying is ideal for short-term storage and transportation.

MSW in developing countries usually contains high moisture content due to the presence of a major component of food waste. The moisture content of MSW greatly influences its biodrying performance, while excess moisture in the waste matrix can limit oxygen transport into the waste pile, low moisture will inhibit microbial activity (Cai *et al.*, 2018). In addition, organic waste degradation, which involves biodrying with natural aeration, is often plagued by limited oxygen supply. Forced aeration, either positive or negative, can ensure sufficient oxygen is supplied for biodrying. Positive aeration is the process in which air is blown upward through waste material, whereas negative aeration involves air being drawn down through waste material. Both methods have advantages and disadvantages; however, previous studies have shown that negative aeration causes a higher ratio of water loss-to-volatile solids (VS) loss relative to positive aeration, which may occur due to greater VS degradation in positive aeration (Shao *et al.*, 2012; Payomthip *et al.*, 2020). In addition, Tom *et al.* (2016a, 2016b) and Colomer-Mendoza *et al.* (2013) observed non-homogeneous moisture distribution after biodrying using positive ventilation methods due to the condensation of evaporated water back into the reactor.

Under high-temperature environments, biodrying requires higher microbial activity levels to degrade organic materials and release metabolic heat. During heating, airflow from positive or negative aeration reduces the moisture content; thus, increasing the flow rate could also increase drying efficiency. A previous study has shown that peak temperature can be reached within the first few days of operation and will persist during the biodrying process with appropriate aeration (Payomthip *et al.*, 2020; Payomthip, 2021). Excessive aeration can increase water evaporation via convection, however, this does not necessarily yield an effective biodrying process. Thus,

aeration must be optimized to remove moisture quickly while also conserving the most organic matter in the treated waste for biofuel usage.

Previous studies have reported the development of the biodrying process for RDF production from MSW using a windrow pile (Sutthasil *et al.*, 2020; Wangyao *et al.*, 2021). However, these technologies are inefficient and require long operation times, i.e., 1–9 months for process completion; additionally, some final products failed to meet end-user standards. Thus, criteria to optimize the biodrying process are needed to ensure the quality of the final product with short operation times. To date, no clear criteria for optimal biodrying of high-moisture waste have been reported, especially using negative aeration mode. This information is essential for the application of biodrying technology in developing countries where high moisture waste is ubiquitous. Therefore, the objectives of this study were to investigate the optimal aeration for biodrying of high moisture MSW under the negative aeration mode and evaluate how this affects the temperature development and characteristics of the treated waste, ensuring the resulting RDF achieves local standards in the minimum time. This study is the first of its kind to present optimized aeration mode biodrying parameters for RDF production in the minimum time and has important implications for MSW treatment both in Thailand and other developing countries.

2. Materials and Methods

2.1 Case study in Thailand

MSW generation in Thailand is growing due to urbanization, population growth, and economic development, increasing the demand for proper waste treatment and disposal facilities. In 2020, Thailand produced 25.37 million tons of MSW with an average generation rate of 1.05 kg/person/day. Despite this growing waste production, properly discarded and recycled waste account for only 36% and 33%, respectively, of the total waste generated. Furthermore, the relative proportion of recycled MSW decreased by 11% compared to the previous year due to the prohibition of MSW sorting by scavengers to prevent disease from spreading at waste disposal sites. As a result, approximately 31% of the generated MSW was improperly eliminated, a significant increase from the 22% recorded the previous year (PCD, 2020a).

Incorporating Waste to Energy (WtE) approaches would help to improve MSW management as well as benefit climate change mitigation plans in the country. In Thailand, the Bio-Circular-Green (BCG) Economy model promoted by the government aims to empower local economies by increasing the gross domestic product through the use of eco-friendly technologies. While other alternative energy sources, such as solar power, have been widely promoted (Wattana *et al.*, 2021), the application of WtE technologies derived from MSW, especially biodrying, remains limited.

2.2 Feedstock preparation

In this study, pre-shredded waste was collected randomly from an MBT plant in Saraburi province, Thailand. The pre-shredded waste was passed through the bag-opening process and fed to a lysimeter with 300 kg/m³ (w/w) density. The quartering method was used to analyze the composition of waste materials (ASTM D5231–92, 2016).

2.3 Experiment setup and operation

The experiments were performed in three lysimeters, each of which was 2 meters in height and 0.5 meters in length and width. All lysimeters were insulated using polyurethane foam. A perforated plate was placed above the bottom of the lysimeter to enhance aeration and support the waste materials. An aeration pipe was fixed under the perforated plate to provide aeration. A u-trap was also installed at the bottom of the lysimeter to collect leachate. The perforated sampling pipes had a diameter of 12.5 mm and were placed inside the lysimeter at heights of 20, 60, and 100 cm to sample the inner gases (top, middle, and bottom layers, respectively). A schematic of the biodrying lysimeter apparatus is shown in Figure 1.

Three lysimeter trials (T1, T2, and T3) were performed under different conditions. First, continuous negative aeration was supplied in all trials over the first 48 hours (days 1 to 2) at 0.5 m³/kg_{waste}/day. Next, aeration values of 0.5, 0.75, and 1.0 m³/kg_{waste}/day were provided in trials T1, T2, and T3, respectively, from the end of day 2 until day 4. Finally, after day 4, an aeration rate of 0.5 m³/kg_{waste}/day was supplied in all lysimeters until the end of the experiment (seven days in total). Table 1 lists the experimental conditions used for each trial.

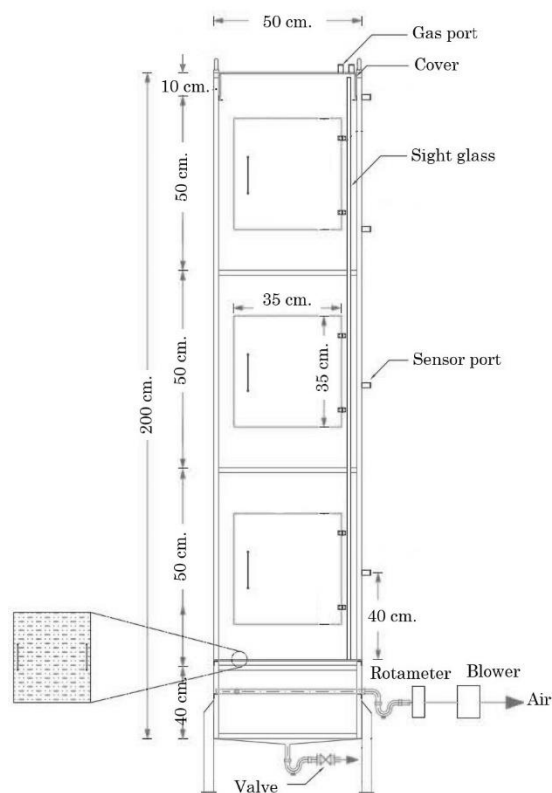


Fig. 1 Schematic of the lysimeter columns in the biodrying trials.

Table 1
Experimental conditions

Trial	Aeration rate (m ³ /kg _{waste} /day)			Total volume (m ³)
	Phase 1 0 – 48 h	Phase 2 48 – 96 h	Phase 3 96 – 168 h	
Trial 1 (T1)	0.50	0.50	0.50	315
Trial 2 (T2)	0.50	0.75	0.50	360
Trial 3 (T3)	0.50	1.00	0.50	405

2.4 Experiment monitoring

The temperature was measured using type-K thermocouples (temperature range of -270°C to 1,327°C) at 20, 60, and 100 cm heights. The temperature was recorded hourly using a data logger (Graphtec GL200A Midi Data Logger; DATAQ Instruments, Akron, OH, USA). The weight of the waste materials was measured daily using a push gantry hoist and digital crane scales. The oxygen (O₂) concentration in the exhaust air was monitored daily using a Biogas 5000 gas analyzer (Geotechnical Instruments International, Ltd., Berlin, UK).

2.5 Sampling and analytical methods

The initial waste materials from the studied site were homogenized, and three samples were collected and placed into sealed bags and subjected to laboratory analysis. After the final day of the experiment, the waste materials were removed from each trial and homogenized manually. Three samples were collected from each trial and placed into sealed bags. The collected samples were used to determine the moisture content, volatile matter content, heating value, and ash content. The water, volatile solids, and ash were analyzed using a thermogravimetric analyzer (TGA801; LECO Corporation, St. Joseph, MI, USA) according to the ASTM D7582 standard. The calorific values were tested using a bomb calorimeter (AC-500 calorimeter, LECO®, USA) according to ASTM D240.

The exhaust gases carbon dioxide (CO₂) and methane (CH₄) were measured daily using the open flux technique. First, a sample was collected and moved to a Tedlar bag using an MP-2N mini pump (Sibata Scientific Technology Ltd, Japan). Next, the emissions were analyzed using a GC Clarus-580 gas chromatographer (PerkinElmer, Waltham, MA, USA). Using the ideal gas law, the gas concentrations were converted to mg/L units at one atmospheric pressure (1,013 hPa).

2.6 Biodrying process performance

2.6.1 Temperature integration index

Temperature is an important bioprocessing parameter because it affects the biodegradation and evaporation of water in municipal solid waste. The temperature integration (TI) index was applied to describe the trial's temperature development. The TI is defined by equation (1):

$$TI = \sum_{t=1}^n (t_{wt} - t_{amb}) \times \Delta t \tag{1}$$

where t_{wt} is the MSW temperature at time t (°C), t_{amb} is the ambient temperature at time t (°C), and Δt is the time step.

2.6.2 Weight loss

The initial and final waste material were weight to calculate the percentage weight loss in different operating conditions using equation (2), which is related to moisture content reduction after the drying process.

$$Weight\ loss = (\Delta W / W_i) \times 100 \tag{2}$$

Where ΔW is the difference between initial and final waste material weight (kg), and W_i is the initial waste material weight (kg).

2.6.3 Gas emission

This study determined gas emissions (CO₂ and CH₄) using the dynamic flux method. Four gas emission samples were collected and kept in Tedlar bags, and their average values were reported. The gas concentrations were measured at the lysimeter inlets and outlets. The concentration of each gas is given by equation (3):

$$OF = (C_o - C_i) \times \frac{Q}{A_{OF}} \quad (3)$$

where OF is the gas emission rate (g of gas emission/m²/h), C_o is the outlet gas concentration (g of gas emission/m³), C_i is the inlet gas concentration (g of gas inlet/m³), Q is the aeration rate (m³/h), and A_{OF} is the enclosed emission area (m²).

2.6.4 Biodrying index and biody-air ratio

Biodrying aims to remove water from waste with minor VS degradation. To indicate the efficiency of the biodrying process, the biodrying index (BI) was calculated using equation (3):

$$BI_t = \frac{WL_t}{VSL_t} \quad (4)$$

where BI_t is the biodrying index at time t, and WL_t and VSL_t are, respectively, the water loss and volatile solid loss in grams at time t.

The biody-air ratio (BA ratio) was used to describe the correlation between the composting process and the biodrying process. Biodrying is a partial composting process, thus, aeration can be related to the air quantity applied during composting. Accordingly, the BA ratio indicates the ratio of aeration—an appropriate approximation of biodrying—to the stoichiometric air demand of the composting process. This ratio is calculated using equation (5):

$$BA \text{ ratio} = \frac{NV_{air}}{Stoi_{air}} \quad (5)$$

where NV_{air} and Stoi_{air} are the aeration input to the biodrying process (m³) and stoichiometric air demand of the composting process (m³), respectively.

2.7 Statistical analysis

To compare the temperature differences between the trial, statistical analysis was performed; specifically, the temperature profiles in different waste layers during each phase and across the whole biodrying process were evaluated. The statistical analysis was performed using SPSS 21.0 software (SPSS Inc., Chicago, IL). The standard deviation was reported along with the average value. The significant differences in trials were tested using one-way ANOVA (Analysis of Variance) with a 95% confidence level (P<0.05).

2.8 Environmental Impact from the biodrying process

The environmental impact assessment from the biodrying process was calculated based on the methodology tools of "Thailand voluntary emission reduction program (T-VER)" under the Thailand Greenhouse Gas Management

Organization (Public Organization). This method has used the tools and methodology based on IPCC and CDM to suit Thailand's circumstances. The greenhouse gas emission from the conventional landfill was calculated based on equation (6), which was only CH₄ generated in the landfilling method by the decomposition of organic waste in landfills under specific anaerobic conditions.

$$BE_{CH_4} = W \times (\rho_w \times 4.02 + \rho_p \times 3.72 + \rho_f \times 1.00 + \rho_t \times 2.23 + \rho_l \times 1.68) \times CF \times 0.1 \quad (6)$$

where BE_{CH₄} emission is the methane gas the emitted from the closed landfill (tCO_{2e}), W is the mass of waste material subjects to the biodrying process (ton) ρ_w is the fraction of wood in waste material (-), ρ_p is the fraction of paper in waste material (-), ρ_f is the fraction of food waste in waste material (-), ρ_t is the fraction of textile in waste material (-), ρ_l is the fraction of branches and leaves in waste material (-), and CF is the factor based on methane correction factor (MCF) in solid waste management site (default 7.14 with MCF equal to 1.00)

The greenhouse gas emission (GHG) from the biodrying process was calculated based on equation (3). The CO₂, CH₄, and N₂O was determined and the OF was then calculated to gas emission using equation (7):

$$PE_{Biodry} = (OF_x \times A_{OF}) \times \Delta t \times GWP_x \quad (7)$$

where PE_{Biodry} is the emission gas from the biodrying process (tCO_{2e}), OF_x is the gas X emission rate (g of gas emission/m²/h), Δt is the duration time of the biodrying process (hour), and GWP_x is the global warming potential of gas X (default of CH₄, CO₂, and N₂O is 28, 1 and 265, respectively).

3. Results and Discussion

3.1 Evolution of temperature and oxygen during the biodrying process

The temperature values at each height in the MSW matrix are shown in Figure 2. The temperature increases due to heat development in the substrate mass as biodrying is a bio-oxidative microbial degradation process. The maximum temperature values ranged from 62.0 °C to 71.2 °C. These temperatures are sufficiently high to kill the majority of enteric pathogens, resulting in a pathogen-free final product; this is consistent with the study of Bernal et al. (2017), who reported that compost temperatures should exceed 55 °C to ensure that pathogens are killed.

The temperature evolution comprises three stages: (1) the heating phase, (2) the high-temperature maintenance phase, and (3) the cooling phase. The heating phase occurred during days 1 to 2, the maintenance phase occurred from days 2 to 4, and the cooling phase occurred from day 4 to the end of the experiment. An increase in temperature indicates an increase in microbial activity, with microbial respiration breaking down the decomposable materials from days 1 to 4. T1 reached its peak temperature of 65.5 °C within two days at 20 cm (bottom level). However, T2 reached a peak value of 62.0 °C on days 2 and 3 at 60 cm (middle level). T3 exhibited a maximum temperature of 71.2 °C at 20 cm (bottom level) on day 3. Thus, T1 had a shorter heating phase than T2 and T3. The temperatures recorded at the bottom and middle levels of trials T2 and T3 were higher than those at

the top level. This also was observed by Tom et al. (2016a, 2016b), who reported minimum temperatures in higher levels at heights of 120 to 240 cm above biodrying trials of mixed MSW. T1 had a more homogeneous temperature distribution than T2 and T3, with similar temperatures recorded throughout the study.

In terms of the homogeneous temperature layers, the temperature differences between waste layers were analyzed and a statistically significant difference was identified between the top and bottom layers ($p < 0.05$) and the middle and top layers ($p < 0.05$). In contrast, no significant temperature difference was detected between the top and middle layers ($p = 0.98$).

Interestingly, a significant difference in all temperature layers was observed in T2, showing the effect of excessive aeration on biodrying ($p < 0.05$). However, no significant difference was measured between the middle and bottom layers in T3 ($p = 1.00$) despite a significant difference between the other temperature layers. Thus, excessive aeration increases heat dispersion in the top and middle layers of waste materials. In contrast, effective heat dispersion was achieved inside the top and middle layers using continuous aeration.

The significance values for all phases are shown in Table 2. The third phase of T1 exhibited an insignificant difference between temperature layers ($p > 0.05$); however, T2 and T3 showed significant temperature differences between the layers ($p < 0.05$), indicating the homogeneity of the biodried product. The temperature evolution in the process varied, corresponding to the degradation rate and organic content, which relate to the heat created by aerobic degradation during the trial. The aeration technique involved applying the same volume from days 0 to 2; however, the recorded temperature evolution of T1, T2, and T3 differed. Inhomogeneous initial waste materials could potentially account for this difference. The initial waste materials were then divided into the three piles used for each trial; this division step could potentially have led to some differences between the samples used in T1 to T3.

The standard deviation values of the temperature levels were calculated to understand temperature

fluctuations. The results show that the lowest standard deviations achieved in T1, T2, and T3 were 1.96, 5.74, and 6.48, respectively. This suggests that continuous negative aeration (T1) leads to high-temperature homogeneity during biodrying in contrast to excessive negative aeration (T2 and T3).

The optimum oxygen concentration value for aerobic degradation is in the range of 15% and 20%, as recommended by Pilnáček *et al.* (2021). Oxygen concentrations below this threshold would result in inefficient, anaerobic conditions; therefore, the concentrations used in this study ensured microorganisms had a constant oxygen supply to maintain their metabolic activity. There was no CH_4 detected in any trials, further confirming that sufficient oxygen was supplied. A high average O_2 concentration was present from days 1 to 2 and remained at about 15–16% until the final day of the experiment, thus confirming that sufficient oxygen was present for negative aeration during the biodrying process.

3.2 Temperature integration index

TI was calculated using the average temperature of each trial, with the TI trends presented in Figure 3. T1 exhibited the highest TI value (365.6 °C), followed by T3 and T2 (346.2 °C and 318.0 °C, respectively). These TI values are notably lower than those reported in other studies, where higher TI values corresponded to longer biodrying times. Shao *et al.* (2012) reported TI values between 432.0–542.0 °C, corresponding to a processing time of 14 days, while Yuan *et al.* (2017) reported values of 523.7–603.5 °C for a processing time of 21 days. A lower TI value of 150.0 °C was reported by Mohammed *et al.* (2017) after seven days of biodrying; this TI was related to heat generated by microbial degradation, implying the self-heating capability of waste materials, and was also associated with biodrying treatment time. In the present study, the differences in TI values between trials were found to be not significant ($p > 0.95$).

Table 2
Significance values for the temperature layers in all trials

Trials	Duration			
	7 days	Phase 1	Phase 2	Phase 3
Trial 1				
Top layer – Middle layer	0.98	0.15	<0.05	0.49
Top layer – Bottom layer	<0.05	0.81	<0.05	0.10
Middle layer – Bottom layer	<0.05	<0.05	<0.05	0.08
Trial 2				
Top layer – Middle layer	<0.05	<0.05	<0.05	<0.05
Top layer – Bottom layer	<0.05	<0.05	<0.05	<0.05
Middle layer – Bottom layer	<0.05	<0.05	<0.05	0.96
Trial 3				
Top layer – Middle layer	<0.05	<0.05	<0.05	<0.05
Top layer – Bottom layer	<0.05	<0.05	<0.05	<0.05
Middle layer – Bottom layer	1.00	0.51	0.10	<0.05

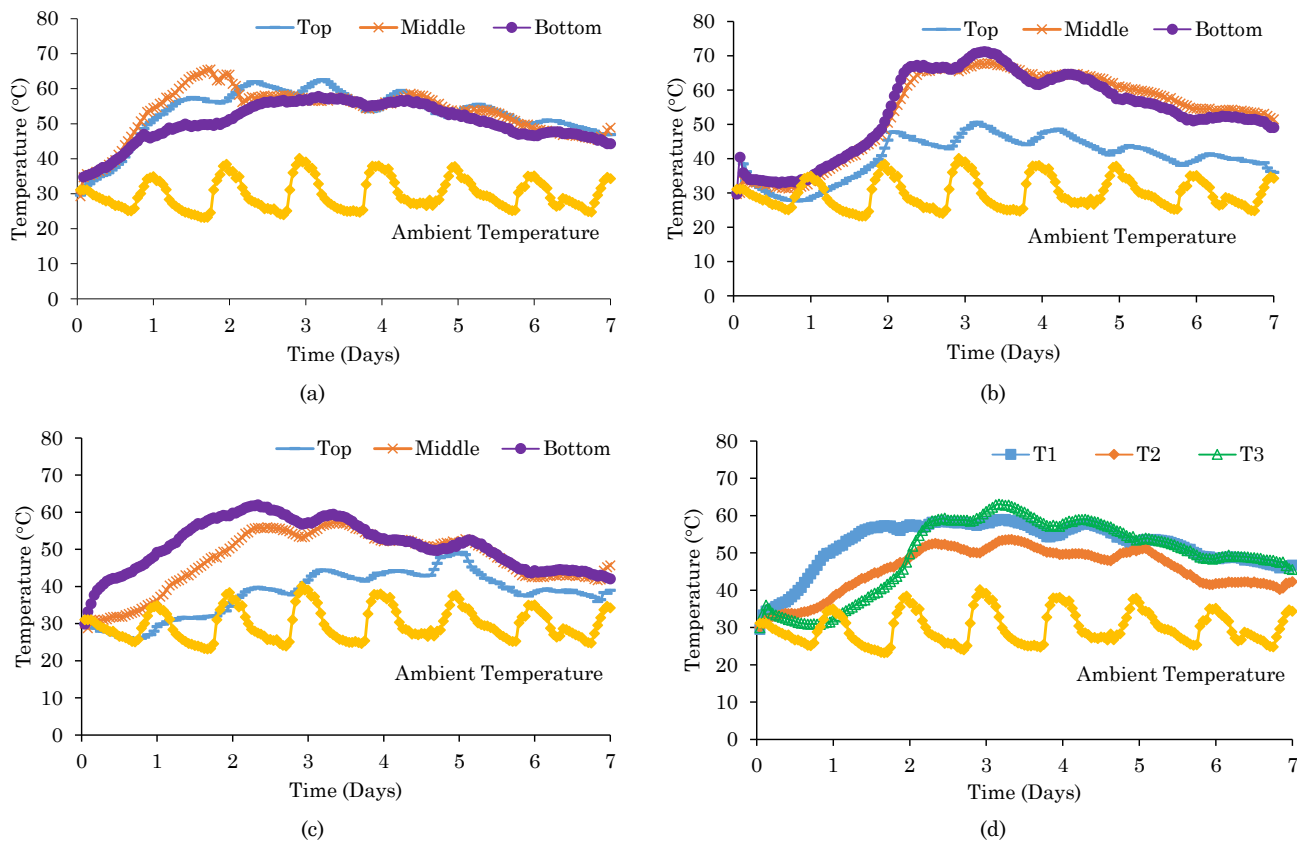


Fig. 2 Temperature evolution during the biodrying process for (a) T1, (b) T2, (c) T3, and (d) their cumulative average temperatures

The TI values of the three biodrying phases are compared in Figure 4. In the first phase (constant aeration rate in all trials), the TI value in T1 was higher than in T2 and T3, consistent with the temperature evolution. However, the differences between the trials were not significant ($p=0.99$ between T1 and T2, $p=0.98$ between T1 and T3, and $p=1.00$ between T2 and T3). In the second phase, a similar TI was identified in all trials, even though the aeration rates were higher in T2 and T3, indicating excessive aeration did not initiate additional biological reactions. The differences among all trials were not significant ($p>0.99$). The phase 3 TI follows a similar pattern, with insignificant differences recorded among the trials ($p>0.99$). The similar TI values for the whole process and each phase between the trials (Table 3) suggest that excessive aeration does not improve biodrying efficiency.

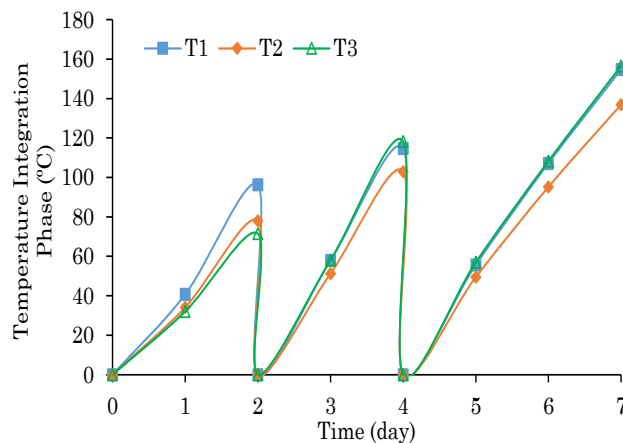


Fig. 4 Three phases of temperature integration during the biodrying process

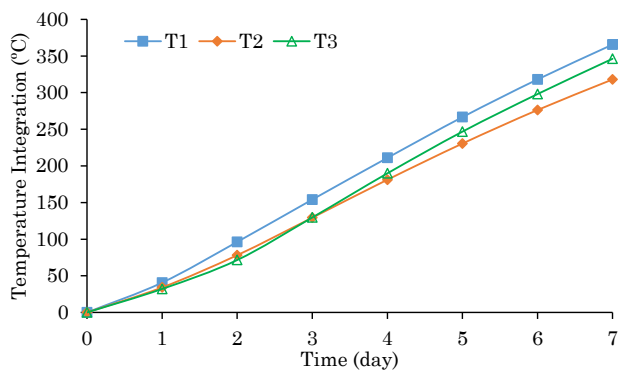


Fig. 3 Temperature integration during the biodrying process

Table 3 Statistical significance of temperature integration between trials

Trials	Duration			
	7 days	Phase 1	Phase 2	Phase 3
T1 – T2	$p>0.95$	$p>0.95$	$P>0.99$	$P>0.99$
T1 – T3	$p>0.95$	$p>0.95$	$P>0.99$	$P>0.99$
T2 – T3	$p>0.95$	$p>0.95$	$P>0.99$	$P>0.99$

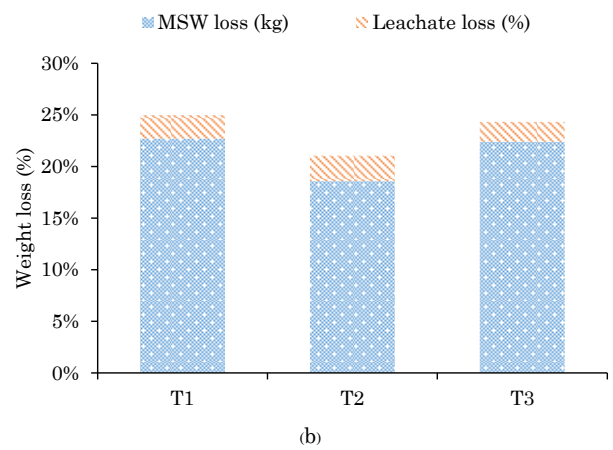
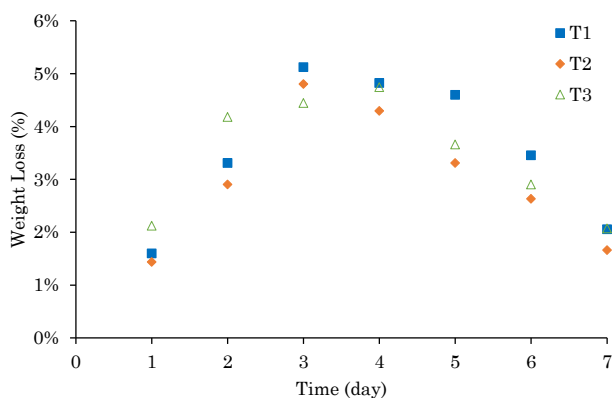


Fig. 5 (a) Daily weight loss during biodrying and (b) total weight loss after the biodrying process

3.3 Weight loss

The weight loss values during each experiment are shown in Figure 5, with T1, T2, and T3 having initial weights of 90, 88.5, and 90.21 kg, respectively. The greatest weight reduction occurred during T1 (24.97%), followed by T3 and T2 (24.32% and 18.63%, respectively).

During the second phase, the aeration rates were 1.5 and 2 times greater for T2 and T3 than the rate for T1; however, the greatest weight loss was observed in T1 on days 3 to 4. The total weight reduction was lower for T2 and T3 than for T1; thus, excess forced air does not effectively remove moisture from waste material. During the third phase, where the aeration rate was adjusted to the base rate, the weight loss in T1 gradually decreased until the final day of the experiment, thus demonstrating that regular aeration removed more water than excessive aeration. This is consistent with the greatest temperature homogeneity recorded in T1.

In addition to these observations, leachate production was similar between trials, showing a 0.35% maximum difference. The highest leachate production occurred in T1, followed by T2 and T3, indicating that excessive and ordinary aeration rates yield similar leachate levels.

3.4 Exhaust gases

The gas emission rate was calculated in terms of the carbon content. Carbon loss during T1 was 0.17 kg, whereas T2 and T3 experienced carbon losses of 0.92 kg and 1.24 kg, respectively. Thus, T1 emitted less greenhouse gas than T2 and T3.

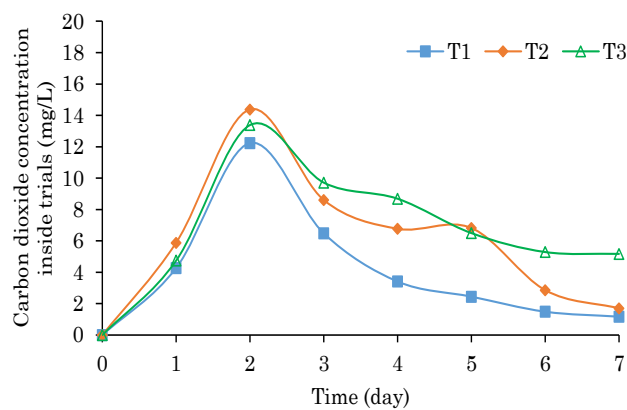


Fig. 6 Daily carbon dioxide concentrations of each trial

The lowest CO₂ level was recorded in T1 (Figure 6), indicating lower microbial activity than in T2 and T3, despite similar temperature evolutions among the trials. T1 had the highest temperature uniformity between the top and middle layers and the highest consistency in phase 3. This may be due to higher microbial activity levels in T2 and T3 than in T1. However, the cooling during T2 and T3 was also affected by the excessive aeration provided during the second phase of the experiment. Thus, the differences between the temperature trends of each trial were negligible.

3.5 Product characteristics

During T1, the moisture content was reduced by 65.6%, and the moisture content decreased from its initial value of 48.5% to a final moisture content of 22.2% within seven days (Table 4). The moisture content values decreased by 49.9% and 60.8% for T3 and T2, respectively. The final moisture content of the RDF should not exceed 30% to prevent biodegradation. When the moisture content is below 35%, microbial activity slows down, yielding a low respiration index (Ragazzi *et al.*, 2012). Comparing the low heating value (LHV) of the RDF with local cement industry requirements, the biodried products obtained from T1 and T3 are acceptable fuels for energy recovery. However, the RDF obtained from T2 did not meet local RDF standards as its final moisture content (30.8%) is 0.8% higher than the maximum permissible value. The final moisture content in T1 was 14.2%—the lowest among the three trials.

T1 achieved the highest LHV of 4,938.0 kcal/kg, increasing 73.63% during biodrying. The LHVs of T2 and T3 were 3,711.5 and 4,451.0 kcal/kg, respectively. The T2 and T3 values do not meet the Thailand's local RDF-3 standard which sets a minimum threshold of 4,500 kcal/kg. However, the LHVs for all trials were in the RDF heating value range for calciner considered by cement companies, i.e., 3,162–4,479 kCal/kg (International Finance Corporation., 2017). Nevertheless, considering the RDF heating value range for main burners (i.e., 4,742–6,060 kCal/kg), only the product obtained from T1 fell within this range. The LHV increased more for T1 than it did for T2 or T3.

Table 4
The MSW characteristics before and after the biodrying process for each trial

Trials	Low heating value (kCal/kg)		Moisture content (%)		Volatile solid (%)	
	Initial	Final	Initial	Final	Initial	Final
T1		4,938.0 ± 10.3%		22.2 ± 12.6%		64.2 ± 10.1%
T2	2,844.0 ± 14.1%	3,711.5 ± 4.9%	48.5 ± 10.6%	30.8 ± 11.3%	49.6 ± 3.4%	59.4 ± 10.6%
T3		4,451.0 ± 2.3%		25.0 ± 9.6%		61.2 ± 8.6%

3.6 Biodrying index and biody-air ratio

Biodrying aims to remove water from waste with minor VS degradation. In these experiments, VS degradation occurred in all trials. T1, T2, and T3 had VS reduction values of 2.87%, 5.43%, and 6.54%, respectively; the final VS contents were between 48.4% and 52.5%. The VS reduction results are consistent with those of previous investigations (e.g., Kristanto *et al.*, 2017; Mohammed *et al.*, 2017; Villegas *et al.*, 2014). Most of the remaining carbon was hard-to-degrade organic carbon (Sutthasil *et al.*, 2020), which requires chemical decomposition.

The BI values ranged from 8 to 20.51 (Table 5). The highest BI was recorded in T1 (20.51), followed by T3 and T2 (8.30 and 8.00, respectively). The maximum BI was within the 1.75 to 20 range reported in previous literature (Huiliñir *et al.*, 2015; Mohammed *et al.*, 2017; Sen *et al.*, 2015; Yang *et al.*, 2014; Yuan *et al.*, 2017). Higher aeration intensity may result in more water removal, with less biodegradation of organic content (Zhang *et al.*, 2020). Thus, lower BI values may indicate inadequate oxygen supply during biodrying, whereas high BI values result in physical dryness.

The BA ratio was related to the air quantity applied during the biodrying process. T1, T2, and T3 had BA ratios of 1.22, 1.33, and 1.82, respectively; thus, the aeration required for biodrying was 122%, 133%, and 182% of the aeration required for composting. Aeration is the primary variable that controls biodrying: higher BA ratios may result in physical drying, whereas lower BA ratios cause decomposition with insignificant moisture loss. The BA ratio increased as the aeration supplied increased. Since physical drying occurs at a BA ratio of 1.55 (Payomthip., 2021), the aeration provided for biodrying should not exceed 155% of that required for composting. Thus, the results indicate that physical drying occurred in T3, while T1 and T2 experienced biodrying only.

Table 5
Biodrying index and biody-air ratio

Trials	Biodrying index	Biody-air ratio
T1	20.51	1.22
T2	8.30	1.33
T3	8.00	1.82

3.7 Economic, and environmental aspects of WtE in Thailand

Several obstacles remain that must be overcome to achieve wider utilization of MSW as an energy source in Thailand. These obstacles are high moisture content in MSW, insufficient promotion measures to attract investment in WtE facilities, and lack of community cooperation in waste segregation. Occasionally, ineffective communication between the government and the general public has also led to opposition to the development of new waste treatment activities (PCD, 2020b). Furthermore, most developing nations' WtE facilities are limited by inadequate infrastructure, pollution control systems, and maintenance (Kumar *et al.*, 2017). Additionally, the shortage of financial and logistical planning and a solid policy framework for WtE have resulted in several project failures that have alienated the public and investors in these technologies. (Kalyani *et al.*, 2014).

Economic analysis has confirmed that investment activities utilizing RDF fuel could bring multidimensional benefits to the natural environment due to reduced emissions and the utilization of ecological waste (Rajca *et al.*, 2020). Municipalities frequently rank financing waste management as one of their top priorities. Operational costs necessitate a robust cost-recovery system to achieve long-term viability (Kaza *et al.*, 2018); however, WtE technologies represent better investment opportunities than continuing to dump waste in landfills (Agaton *et al.*, 2020).

The results of the GHG emission from the biodrying process comparing to the conventional method (landfill) is presented in Table 6. The GHG emissions from the landfill was higher than the GHG emissions produced from biodrying process. The GHG from the biodrying process was at 0.05, 0.26, and 0.36 tCO_{2e}/ton_{waste} in T1, T2, and T3, respectively. While GHG emissions from the landfill was 0.75 tCO_{2e}/ton_{waste}. In total, GHG emissions was maximize reduced 0.70 tCO_{2e}/ton_{waste} or 93.3 % in T1.

Biodrying can treat waste materials with high moisture contents, including food waste. Compared to conventional method (landfill), the biodrying process produces relatively little greenhouse gas and the final product can be used as an alternative fuel. If this technology is adopted; for example, in Thailand's case, where the waste was treated by landfill at about 7.86 million ton in year 2020. The landfill method will be produced GHG emissions about 5.93 million tCO_{2e} whereas only 0.4 million tCO_{2e} of GHG emissions will be released from the biodrying process.

Table 6
Environmental impact from the biodrying process

Trials	Greenhouse gas emission (kgCO _{2e} /kg _{waste})			
	CH ₄	CO ₂	N ₂ O	Total
Landfill	0.755	-	-	0.755
T1	0.001	0.049	-	0.051
T2	0.002	0.263	-	0.265
T3	0.003	0.354	-	0.357

4. Conclusion

This study demonstrated a practical application of biological drying processes with low investment costs and simple operation. It is suitable for application to unsorted MSW containing high moisture levels that is typically found in many developing countries. The air supply for biodrying was optimized under the negative operation mode and evaluated in terms of temperature profiles, final product quality, and operation time. The continuous aeration mode was found to achieve optimal biodrying, whereas excessive aeration did not improve the biodried product quality. Under optimal operation, the biodried product met local RDF-3 standards within seven days under continuous aeration.

The temperature evolution recorded in this study indicates microbial activity in the trials, where continuous aeration without excessive air exhibited the shortest heating phase and maximum homogeneity of waste material. The constant temperature layer recorded in the cooling phase signals the completion of the biodrying process, with no significant temperature differences identified between different layers in the trial under continuous aeration. The non-significant TI differences between the aeration patterns showed that excess aeration did not initiate homogeneity during biodrying. Thus, continuous aeration represents the optimal biodrying operation, whereas excessive aeration does not affect the biodried product.

Considering the LHV of the RDF-3 standard for cement plants, the biodried product from continuous ventilation (T1) was acceptable according to the RDF-3 standard, whereas the RDFs obtained from T2 and T3 did not meet this standard. Therefore, the quality of RDF can be improved 1.7 times within a short period (seven days) to meet Thailand's standards with homogeneous temperature distribution under continuous aeration.

The aeration required for biodrying was 22% higher than the theoretical air requirement calculated from the stoichiometric equation using negative aeration mode to achieve RDF that meets the Thai standards within 7 days. Further increases in air supply did not improve the quality of RDF but led to the physical drying phenomenon. The BI, as well as the BA ratio, were successfully adopted to evaluate the biodrying performance in this study.

In terms of future research, it is recommended that further studies are carried out at a larger scale to study the effect of waste compaction and odor release during the operation of full-scale biodrying processes. In addition, this study only used MSW from one site; future work could perform a comparative analysis between different locations to achieve more robust results. Despite these

limitations, the findings represent a detailed characterization of RDF production parameters and form an important reference point for future MSW processing work, both locally in Thailand and other developing countries.

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